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COMPARISON OF COMPUTER CODES FOR CALCULATING DYNAMIC LOADS IN WIND TURBINES

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NOTICE

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ABSTRACT

Seven computer codes for analyzing performance and loads in large, horizontal-axis wind turbines were used to calculate blade bending moment loads for two operational conditions of the 100 kW Mod-0 wind turbine. Results are compared with test data on the basis of cyclic loads, peak loads, and harmonic contents. Four of the seven codes include rotor-tower interaction and three are limited to rotor analysis. With a few exceptions, all calculated loads were within 25% of nominal test data.

INTRODUCTION

The development of computer codes for calculating dynamic loads in horizontal-axis wind turbines has been part of the Federal Wind Energy Program for almost four years. In December of 1973 an existing helicopter blade analysis code called MOSTAB was modified for wind turbine application under government contract, producing a code called MOSTAB-WT (ref. 1). Although it contained only one aeroelastic degree of freedom, MOSTAB-WT was found to be extremely useful in the design of the Mod-0 wind turbine (ref. 2). It was also used for load studies comparing teetered and rigid rotors (ref. 3) and upwind and downwind rotor locations (ref. 4). However, codes with multiple degrees of blade freedom which include other components such as the drive train, the controls, and the tower were needed in order to design advanced wind turbine systems.

To meet this analysis need the Energy Research and Development Administration (ERDA) has sponsored the development of at least six codes (in addition to MOSTAB-WT) by NASA and its contractors. As might be expected in an area of new technology, these codes differ considerably in approach and technique. At this time it is appropriate to compare the various codes in their present state of development to determine advantages and disadvantages of each. Because of the generally complicated nature of any structural dynamics analysis, a detailed comparison of seven computer codes is extremely difficult. Therefore, the objectives of this study have been limited to the following: (1) To present a brief overview of each code and identify sources for further detailed information, and (2) to compare the performance of each code against two sets of test data measured on the 100 kW Mod-0 wind turbine, an experimental machine in operation at NASA's Plum Brook Station near Sandusky, Ohio (Fig. 1).

DESCRIPTION OF CODES

The seven computer codes compared in this study are listed in Table 1, together with brief descriptive notes and sources for additional information. All codes are aeroelastic (i.e., air loads and blade deformations are coupled) and include loads which are gravitational, inertial, and aerodynamic in origin. All consider wind shear (wind speed variation with altitude), tower shadow (reduced wind speed downwind of the tower), and inflow angle between rotor axis and wind vector. Some of the special characteristics of each code are as follows:

MOSTAB-WT Code
(MOdular STABility Derivative - Wind Turbine)

As described previously, MOSTAB-WT is a single blade, one-degree-of-freedom (DOF) code (ref. 1). The blade may execute one "flapping" mode, in which deflections parallel to the axis are permitted. Rotor speed is constant and the rotor shaft is assumed to be rigidly supported. The blade's equations of motion are solved in the time domain until a steady-state or "trim" condition is achieved. MOSTAB-WT is the simplest of the seven codes evaluated.

MOSTAB-WTE Code
(MOdular STABility Derivative - Wind Turbine, Empirical)

MOSTAB-WTE is an extension of the MOSTAB-WT code which contains two empirical constants obtained after early Mod-0 test data were compared with MOSTAB-WT load predictions. These constants were introduced for two purposes: (1) To include blade loads induced by tower and nacelle motions not accounted for in the MOSTAB-WT code, and (2) to increase the general level of calculated blade loads so that predicted loads would be equivalent to nominal-plus-1σ measured loads (i.e., predicted loads exceed measured loads 85% of the time, at any given operating condition).

MOSTAB-WTE was first used in November 1976 to predict the effects of a new dual yaw drive system proposed for both the 100 kW Mod-0 and the 200 kW Mod-0A wind turbines (ref. 5). Some of the results of that study are shown in a later section. MOSTAB-WTE equations are given in Appendix A and Table 2 lists the empirical constants used for various structural configurations to date.

MOSTAB-HFW Code
(MOdular STABility Derivative - High Frequency, Wind)

MOSTAB-HFW is an advanced version of MOSTAB-WT in which each rotor blade may have up to four aeroelastic degrees of freedom and the rotor itself may exhibit various degrees of gimballing. However, the support for the rotor is still assumed to be rigid. MOSTAB-HFW is a wind-turbine version of a rotorcraft code called MOSTAB-HFA developed for the Naval Air Systems Command (refs. 6 and 7). Details of the-HFW code may be found in reference 8. The first application of MOSTAB-HFW was in an analysis of the effects of teetering and root flexure on Mod-0 blade loads (ref. 9).

REXOR-WT Code
(Revised and EXtended RotOR - Wind Turbine)

REXOR-WT is a specialized version of a general rotorcraft systems analysis code called REXOR, which was developed for the U.S. Army Aviation Systems Command (ref. 10). It has a capacity for approximately thirty fully-coupled degrees of freedom. Equations of motion for the complete wind turbine -- which can include rotor, drive train, nacelle, tower, and control components -- are solved in the time domain. REXOR-WT produces time histories of loads, deformation, power, etc. in much the same fashion as an analog computer. Thus, both transient and steady-state analyses can be conducted with this code.

REXOR was used to perform a limited analysis of transient and steady-state loads during the design of the Mod-0 blades (ref. 11). REXOR-WT was later used to correlate early Mod-0 test data with calculated loads (ref. 12). In the present study, the REXOR-WT model of the Mod-0 system included three degrees of freedom for each blade, two for the drive train, and two for the combined tower and nacelle.

GETSS Code
(*General Electric Turbine System Synthesis*)

The GETSS computer code was developed by General Electric's Space Division in 1976 as part of the ERDA/NASA Mod-1 wind turbine project now in progress. The Mod-1 wind turbine has a nominal rotor diameter of 200 feet and an electrical output exceeding 1500 kW. During the loads analysis of this machine major emphasis was placed on detailed finite element modeling of major components. Major substructures (tower, bedplate of the nacelle, shaft and rotor hub, and two blades) were modeled in sufficient detail for both dynamic and stress analysis. For example, the Mod-0 wind turbine substructures were modeled with a total of over 700 joints, 4000 degrees of freedom, and 300 modes.

Mode shapes and resonant frequencies for the major substructures are combined using stiffness coupling to determine system mode shapes and frequencies. This is done with non-rotating blades at four different azimuthal positions, 45 degrees apart. The rotational dynamic response is then obtained by a piece-wise linear coupling of the model responses at intervals of 45 degrees. The degree of participation of each mode can be identified as the complete system is excited and responds. Detailed information on the GETSS modeling of the Mod-0 wind turbine is given in reference 13.

F-762 Code

The F-762 code was developed for rotorcraft analysis by United Technology Research Center and used for the structural analysis of fiberglass composite wind turbine blades by Hamilton Standard Corporation. This code is primarily a rotor analysis tool in which the blades are modeled as individual aeroelastic elements connected to a hub which is supported on an elastic foundation. The impedances which describe the elastic foundation are derived from a structural model of the nacelle and tower system. In the F-762 code, equations of motion are solved in the time domain. Thus, F-762 can be used for transient as well as steady state loads analyses.

MOSTAS Code
(MOdular STAbility Derivative, System)

Early recognition of the limitations of the MOSTAB-WT code resulted in a contractural effort between Paragon Pacific Incorporated and the government to provide a complete series of coupled dynamics codes specifically tailored to the solution of wind turbine problems. The result of this effort is a systems code, recently developed, called MOSTAS. The general features of this code are described in reference 14.

MOSTAS analysis begins with the MOSTAB-HFW code described previously which includes a fully nonlinear set of equations which are solved for a given operating condition, presuming a rigidly supported shaft, quiescent control inputs, and constant rotor speed. Next, a sub-program called ROLIM synthesizes a rigorous linear rotor model in periodic coefficients from the MOSTAB-HFW output. The ROLIM rotor model is then combined with linear models for other subsystems (such as the tower) to produce a coupled system model. The coupling subprogram is called WINDLASS. In the process of coupling the rotor to the system, periodic coefficients in the equations describing the rotor behavior are approximated by constant coefficients. Multi-blade coordinates are used to reduce the degree of approximation involved, so errors are expected to be secondary.

MOD-0 DATA CASES

For purposes of establishing reference test data for comparison with computer code calculations, two sets of blade load data have been defined, which were measured on the Mod-0 wind turbine (Fig. 1). These data sets have been designated as Mod-0 Data Cases I and IV. The data sets contain time histories and harmonic analyses of bending moment loads measured in the Mod-0 blades by means of strain-gage load cells. Moment loads in the flatwise and edgewise directions at Station 40 (shank area, 5% span) and Station 370 (midblade area, 49% span) were measured. Additional data are also available for these two cases, including shaft bending and torque loads, nacelle accelerations, and tower deflections. However, for purposes of comparing computer codes, blade moment loads were judged to be critical, so other measured data were not used in this study.

Structural definitions of the Mod-0 components were obtained from the blade manufacturer (ref. 15), from structural drawings of the tower and nacelle, and from manufacturers' data on the drive train elements. These sources were supplemented by stiffness tests of key components which were found to be nonlinear, such as a Falk coupling in the drive train (ref. 6) and the yaw drive system (ref. 5).

Operating Conditions

Figure 2 is a schematic plan view of the wind turbine showing orientation of the nacelle with respect to the tower and the wind. Data Case I, (Fig. 2(a)) with single yaw drive and stairs in the tower, presents a high level of rotor-tower interaction. These data were measured on December 18, 1975. On the other hand, Data Case IV (Fig. 2(b)) with the yaw drive locked (relatively rigid nacelle-to-tower connection) were measured on September 11, 1976, after the tower stairs were removed and therefore exhibit little rotor-tower interaction. Thus, these two cases represent relatively high and low levels of blade loading sustained by the Mod-0 wind turbine operating at nominal wind speeds between 25 and 28 mph.

Typical Time-History Curves

Before presenting the time-history curves which constitute Data Cases I and IV, typical curves will be shown to illustrate sign conventions, terminology and general load behavior. A typical cycle of flatwise bending load during one rotor revolution is shown in Figure 3. A positive flatwise moment bends the blade toward the tower causing tensile stresses on the low-pressure (downwind) surface. In Figure 3, flatwise moment M_y is plotted versus the blade azimuth ψ_b, which is zero and 360^o when the blade points downward. As shown in the figure, the flatwise time history for a rotor located downwind of the tower is dominated by the impulse applied to the blade each time it passes through the tower's wake or "shadow".

For purposes of stress and fatigue analysis it is convenient to define cyclic and steady loads which represent the severity of a given complicated load time history. Definitions of steady load $\bar{M}$ and cyclic load δM are shown in Figure 3, in terms of maximum and minimum loads occurring during one revolution.

Figure 4 illustrates a typical time history of edgewise load, M_z, measured during one revolution. A positive edgewise load on the blade tends to stop the rotor, causing tensile stresses on the blade's leading edge. An edgewise moment time history is usually composed of three components, as shown in Figure 4: (1) A steady bending moment which produces shaft torque and power, (2) a sinusoidal gravity moment caused by the blade's own weight, and (3) high frequency dynamic loads attributable to motions of the nacelle and tower.

Time History Curves, Data Cases I and IV

Figures 5 to 7 show time histories of flatwise and edgewise moments measured at Stations 40 and 370 for Data Cases I and IV. Most of the data are from load cells in Blade No. 2, with some data for Case IV from Blade No. 1 (Fig. 7). The time histories are presented as shaded bands defining upper and lower bounds which enclose data from three consecutive revolutions of the rotor. The abscissa in all cases is the azimuth of Blade No. 2, measured from the vertically downward position.

Comparison of Figure 5 with Figures 6 and 7 shows that Data Case I loads are generally larger, the tower shadow pulses in the flatwise bending loads are more pronounced (because of the tower stairs), and the high frequency harmonics in the edgewise loads are more significant (because of the relatively soft single yaw drive).

Harmonic Analysis

Tables 3 and 4 list the harmonic content of the bending moments which were shown in time-history form in Figures 5 to 7. Harmonic data are given terms of amplitudes and phase angles to be used in the following Fourier series:

$$M = \sum_n C_n \sin (n\psi_b + \phi_n), \quad n = 0, 1, 2, \ldots \tag{1}$$

in which

- M moment load, lb-ft
- C_n amplitude of n^{th} harmonic, lb-ft
- ψ_b azimuth of Blade No. 2, deg.
- ϕ_n phase angle of n^{th} harmonic, deg.

Tables 3 and 4 contain harmonic data for the upper and lower bounds of the data envelope plus an average cycle in which amplitudes and phase angles are averages of the bounding values. These averages are used later for comparison with calculated harmonic contents.

RESULTS AND DISCUSSION

Cyclic Moment Loads

Calculated and measured moment loads will be compared first on the basis of their cyclic components, defined as follows:

$$M_y = \tfrac{1}{2} (M_{y,max} - M_{y,min}) \tag{2a}$$

$$M_z = \tfrac{1}{2} (M_{z,max} - M_{z,min}) \tag{2b}$$

in which the maximum and minimum values are determined for one revolution of the rotor. Figure 8 illustrates how cyclic moments calculated using the seven codes compare not only with the specific data cases defined but also with the trend of data measured over a period of time on the Mod-0 wind turbine. This trend is represented by a nominal variation of load with wind speed plus a band of variation which is estimated to be $\pm 1\sigma$ in width, thereby containing loads for about 70% of the machine's revolutions. This band is approximately equal to ±20% of the nominal loads with the exception of Case IV edgewise loads. Variations are caused by changes in wind direction and velocity, control changes, and unsteady factors not yet identified.

The empirical constants used in the MOSTAB-WTE code were selected to place its results at the top of the variation band, as shown in Figures 8(a) to (d). Data Cases I and IV do not necessarily represent the nominal loads as shown by Figures 8(d) and (c). Other general observations concerning the results shown in Figures 8 are as follows:

1. Loads calculated by all codes fall within the $\pm 1\sigma$ data variation band, with the exception of edgewise loads for Case I which were calculated using the MOSTAB-WT and MOSTAB-HFW codes. MOSTAB codes are able to predict only the gravity component of cyclic edgewise load because shaft motion is absent in these codes.

2. REXOR-WT results generally agree with nominal loads. Results for the GETSS, F-762, and MOSTAS codes tend to be mixed, falling both above and below nominal load values.

Tables 5 and 6 present data for a more complete comparison of measured and calculated cyclic loads. Included are flatwise and edgewise moments for both data cases and both blade stations. In Table 6, moments are normalized with respect to the nominal loads for ease of comparison. The general observations made with respect to Figures 8 apply to the more complete data in these two tables.

Peak Moment Loads

A second comparison of calculated and measured moment loads will be made on the basis of their peak values, defined as the maximum absolute value occurring during one revolution. Steady loads (i.e., average of maximum and minimum values) were not used for comparison purposes because magnitudes of steady load are often small. Peak loads include both cyclic and steady components and in addition are significant for limit load calculations.

Before measured and calculated peak loads can be compared, the measured values must be corrected for zero errors. These errors occur primarily as a result of calibration errors, zero drift of the strain gages in the blade load cells, and errors in the strip-chart recorders. The procedure used to calculate zero error is as follows: It was first assumed that the time-average moments calculated using the MOSTAB and REXOR-WT codes could be combined to give the nominal time-average moments. Then, differences between measured time-averages and these nominal values were assumed to be zero errors. The results of these zero-error calculations are shown in Table 7. The most significant errors occurred in the flatwise moments for Data Case IV.

Once estimates of zero error were obtained, peak nominal moments were calculated by the procedure shown in Table 8. Measured steady moments for Data Cases I and IV were corrected for zero error, giving nominal steady moments. Adding or subtracting nominal cyclic moments from Table 5 and taking absolute values produces the nominal peak moments to be used for comparison and calculated peak values.

Measured and calculated peak moment loads are compared in Tables 9 and 10. Inspection of the ratios between calculated and measured moments in Table 10 shows a wide range of values, from 0.57 to 1.30. Peak moments calculated by means of the MOSTAB-WTE code average 14% above nominal measured moments. This illustrates the level of conservatism introduced into the calculations through selection of appropriate empirical constants (Table 2). MOSTAB-HFW and F-762 code calculations of peak moments are 3% to 5% above nominal, on the average.

The MOSTAB-WT, REXOR-WT, and MOSTAS codes produced peak moments which average 1% to 4% below nominal. Peak loads calculated by means of the GETSS code were the least conservative, averaging 11% below nominal measured peak loads.

Summary of Load Ratios

All the load ratios listed in Tables 6 and 10, for cyclic and peak loads, respectively, were averaged, and the results are given in Table 11. These average ratios signify the general level of conservatism for each code when it is used to predict a blend of high and low blade loads. MOSTAB-WTE, with its empirical constants selected to place calculated loads at the nominal $+1\sigma$ level was found to have an average load ratio of 1.15. This value is somewhat lower than expected. Average load ratios for the six remaining codes were very similar, only varying from 0.94 for the GETSS code to 1.00 for MOSTAB-HFW. Thus, on the basis of an average of all loads calculated, these six codes are not significantly different. With the exception of MOSTAB-WTE, all codes predicted loads equal to or slightly less than nominal loads, on the average.

The codes did differ significantly from each other in the amount of variability in load ratios. This is shown in Table 11 by the root-mean-square deviations for each code. These vary from a high of ±0.24 for the MOSTAB-WT code with its single degree of freedom, to a low of ±0.05 for the REXOR-WT code. The empirical constants added to the MOSTAB-WT code to form MOSTAB-WTE not only raised the average load ratio from 1.00 to 1.15 but also lowered the deviation from ±0.24 to ±0.10. Both of these results are improvements in the usefulness of this simple code for preliminary design purposes. The added degrees of freedom in MOSTAB-HFW also improved the MOSTAB-WT results somewhat, both on the average and with respect to deviation from the average.

Harmonic Contents

A third comparison between code output and test data was made on the basis of harmonic content. Each calculated time-history of load was analyzed harmonically, producing the amplitudes listed in Tables 12 and 13. For comparison purposes, each harmonic amplitude was then normalized with respect to its cyclic load (the sum of all harmonics). These normalized harmonic results are presented in Figures 9(a) to (d) for Data Cases I and IV, respectively.

As shown in Figures 9(a) to (d), the variation in normalized test data with blade station and blade number is usually small. An exception to this is shown in Figure 9(b) for the first harmonic amplitude.

In Figure 9(a) all codes gave the same pattern of harmonic content as the test data, which show continually decreasing harmonic amplitudes with increasing harmonic number. Minor variations in the first harmonic can be seen for the REXOR-WT and the F-762 codes.

Variation among the seven codes and the data were more pronounced for edgewise loads, as shown in Figure 9(b). The even harmonics were generally negligible. Of special interest is the fourth harmonic. Although the edgewise natural frequency of the blades is approximately four per revolution (2.6 Hz) all the system codes agreed with the test data as to the absence of any fourth harmonic load. The third and fifth harmonics were found to be prominent and approximately equal, leading to the empirical equations for edgewise load in MOSTAB-WTE (see Appendix A). The system codes generally predict third harmonic amplitudes equal to or greater than those observed, while the fifth harmonic is generally underestimated.

Figures 9(c) and 9(d) show clearly that for Case IV all codes reproduce the harmonic contents of both edgewise and flatwise loads quite well. However, with the yaw drive locked as it is in Case IV, the dynamic behavior is concentrated in the first harmonic to a much greater extent than in Case I. Case IV illustrates the fact that in a stiffly supported rotor, harmonic content of loads is not very significant. As shown in Figure 9(c), the third and fifth harmonics have been reduced, compared with Case I.

Code Verification

Preliminary criteria for judging whether or not a code is verified in comparison with available test data have been established as follows:

1. Calculated loads, expressed as an average and an RMS deviation from the average, should be within 20% of nominal measured loads.

2. All significant harmonics should be predicted.

Referring to Table 11, the first criterion for verification is met by the following codes: MOSTAB-HFW, F-762, MOSTAS, and REXOR-WT. MOSTAB-WTE appears to meet this criterion with reference to nominal $+1\sigma$ loads, rather than nominal loads. MOSTAB-WT does not contain sufficient degrees of freedom to meet this criterion. The GETSS code would satisfy the criterion easily if all calculated loads were increased by about 5%. With respect to the second verification criterion, that which requires identification of significant harmonics, all codes except MOSTAB-WT appear to meet the requirement.

Load Predictions

The MOSTAB-WTE and REXOR-WT were used to predict the effect on blade loads of a new dual yaw drive system for the Mod-0 wind turbine. The results are shown in Figures 10(a) and (b). The MOSTAB-WTE code provided an estimate of nominal + 1σ cyclic flatwise moment (Fig. 10(a)) in good agreement with data obtained later. Prediction of edgewise load using MOSTAB-WTE (Fig. 10(b)) appears to be somewhat conservative, at least in comparison with load bank data. Additional synchronized operation data are required before the level of conservation can be judged.

The REXOR-WT code was used to predict the nominal cyclic loads for dual-yaw drive operation, and Figures 10 show that predicted and measured loads agreed very well.

SUMMARY OF RESULTS

In this study, seven computer codes for calculating dynamic loads in wind turbines were compared on the basis of calculated blade loads, with steady-state Mod-0 wind turbine data as a standard. Other important factors not considered were code availability and cost, running time and cost, complexity, transient capabilities, and loads in the remainder of the wind turbine. Thus, this study was a partial evaluation of computer codes, and the following conclusions are presented with this in mind:

1. Six of the seven codes studied (MOSTAB-WT and -HFW, MOSTAS, F-762, REXOR-WT, and GETSS) calculated loads which on the average were within 6% of nominal loads measured on the Mod-0 wind turbine.

2. Loads calculated using an empirical code (MOSTAB-WTE) were 15% above nominal levels, in accordance with the objective of this code to provide load margin.

3. Among the system codes evaluated, the REXOR-WT code appeared to be the most consistent in producing calculated loads close to nominal loads.

4. All codes except MOSTAB-WT and -HFW satisfactorily calculated the general pattern of both flatwise and edgewise loads for the two cases studied. These two codes contain the assumption of rigid rotor support which eliminates some edgewise load harmonics.

5. The empirical code MOSTAB-WTE was verified on the basis of comparison with the results of the system codes and test data obtained from the Mod-0 wind turbine with dual yaw drive.

CONCLUDING REMARKS

Special purpose codes for the calculation of dynamic loads in wind turbines are now in an advanced state of development. The four system codes now available (MOSTAS, REXOR-WT, GETSS, and F-762) can be considered to be verified at least for "rigid" or "semi-rigid" wind turbine systems. These systems, like the Mod-0 wind turbine, have tower bending and torsion frequencies above twice the rotor speed. Verification of the codes for "soft" systems with frequencies less than twice the rotor speed remains to be performed. However, no special problems or difficulties are expected which would prevent verification of the four system codes using soft system data.

Three of the codes evaluated (MOSTAB-WT, -HFW, and -WTE) are limited to analysis of rotor loads. However, for rigid or semi-rigid systems, these codes are often sufficient. Use of rotor codes rather than system codes can result in substantial savings in computer time and input data preparation.

APPENDIX A

Derivation of Empirical Equations for MOSTAB-WTE Code

Equations will be derived with which blade loads calculated using the MOSTAB-WT code (one DOF) can be increased to (1) account for nacelle motion effects and (2) place calculated values above an estimated 84% of the cyclic loads measured at a given wind speed (i.e., at the "nominal + 1σ" level).

Flatwise Loads

Examination of early Mod-0 data revealed that MOSTAB-WT cyclic load calculations simulated time-histories of measured loads but differed from test data by a scale factor. Therefore, the first empirical equation in MOSTAB-WTE is simply

$$M_{y,\ WTE} = \alpha_y\ M_{y,\ WT} \tag{A1}$$

in which α_y is an empirical constant and the subscripts WTE and WT refer to the loads calculated by MOSTAB-WTE and MOSTAB-WT, respectively. It was also assumed that all harmonic amplitudes could be scaled equally. Time averages are assumed to be the same for the two codes. Thus, if

$$M_{y,WT} = \sum_n C_{n,WT} \sin\left(n\psi_b + \phi_{n,\ WT}\right) \qquad n = 0, 1, 2, \ldots \tag{A2}$$

and

$$M_{y,WTE} = \sum_n C_{n,WTE} \sin\left(n\psi_b + \phi_{n,WTE}\right) \qquad n = 0, 1, 2, \ldots \tag{A2b}$$

then

$$C_{n,WTE} = C_{n,WT}, \quad n = 0 \tag{A3a}$$

$$C_{n,WTE} = \alpha_y C_{n,WT}, \quad n = 1, 2, 3, \ldots \tag{A3b}$$

and

$$\phi_{n,WTE} = \phi_{n,WT}, \quad n = 0, 1, 2, 3 \tag{A3c}$$

The blade azimuth ψ_b is zero and 360° when the blade points downward.

Edgewise Loads

As shown in Figure 4, edgewise moment loads can contain harmonic components higher than one per revolution which appear to be the result of nacelle and tower motion, principally lateral bending and yawing. These harmonics are generally odd, with only the first, third, and fifth harmonic amplitudes having significant size. In MOSTAB-WTE cyclic edgewise loads in excess of the gravity load are designated as coupled loads and are idealized as follows:

$$M_{z,\ coupled} = \beta \left(\sin \psi_b + \sin 3\,\psi_b - \sin 5\psi_b \right) \qquad \text{(A4)}$$

in which β is a harmonic amplitude assumed to be the same for the first, third, and fifth harmonics. The signs of the individual harmonics are such as to produce the higher-frequency time history shown in Figure 4. The maximum value of the coupled edgewise moment given in Equation (A4) is

$$(M_{z,\ coupled})_{max} = M_{z,\ coupled}(49.5^o) = 2.207\beta \qquad \text{(A5)}$$

Assuming the edgewise moment to be the sum of the three components shown in Figure 4, the cyclic load in MOSTAB-WTE becomes

$$M_{z,WTE} = M_{z,g}(49.5^o) + 2.207\beta \qquad \text{(A6a)}$$

in which $M_{z,g}$ is the sinusoidal gravity load on the blade. Therefore

$$M_{z,WTE} = 0.760\ \delta M_{z,g} + 2.207\beta \qquad \text{(A6b)}$$

in which $\delta M_{z,g}$ is the amplitude of the gravity load.

To evaluate the coefficient β the assumption was made that the cyclic flatwise moment δM_y is the principal cause of nacelle motion, and that the coupled edgewise moment is therefore related to δM_y. This assumption leads to the empirical equation

$$\delta M_{z,WTE} = \delta M_{z,g} + \alpha_z\ \delta M_{y,WTE} \qquad \text{(A7)}$$

in which α_z is an empirical constant. Combining equations (A6b) and (A7) then gives the amplitude of the coupled harmonics, or

$$\beta = 0.109\ \delta M_{z,g} + 0.453\ \alpha_z\ \delta M_{y,WTE} \qquad \text{(A8)}$$

The harmonic content of the edgewise moment loads calculated using the MOSTAB-WTE code then becomes

$$M_{z,WTE} = \sum_n C_{n,WTE} \sin (n\psi_b + \phi_{n,WTE}) \qquad \text{(A9a)}$$

in which

$$\begin{aligned} C_{o,WTE} &= C_{o,WT} \\ C_{1,WTE} &= \delta M_{z,g} + \beta \\ C_{n,WTE} &= 0, \qquad n = 2,4,6, \ldots \\ C_{n,WTE} &= \beta, \qquad n = 3 \text{ and } 5 \end{aligned} \qquad \text{(A9b)}$$

and

$$\begin{aligned} \phi_{o,WTE} &= \phi_{o,WT} \\ \phi_{n,WTE} &= 0, \qquad n \neq 5 \\ \phi_{5,WTE} &= 180^0 \end{aligned} \qquad \text{(A9c)}$$

Equations (A1) to (A3) and (A7) to (A9) constitute the basis of the MOSTAB-WTE code. The empirical constants α_y and α_z appear to depend on (1) the lateral and yawing stiffness of the tower nacelle system, and (2) the natural frequency of the tower/nacelle system compared with the product of the number of blades and the rotational speed of the rotor. Table 2 lists empirical constants used to date for various Mod-0 configurations.

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Table 1. - Computer codes presently used for aero-elastic analysis of dynamic loads and deformations in horizontal axis wind turbines.

Code	Type (domain)	Source for Information
MOSTAB-WT	Single blade; 1 DOF [a] (time)	Mr. Barry Holchin Mechanics Research Incorporated 9841 Airport Boulevard Los Angeles, CA 90045
MOSTAB-WTE	Same, plus empirical constants	Dr. David A. Spera NASA-Lewis 49-6 21000 Brookpark Road Cleveland, Ohio 44135
MOSTAB-HFW	Rotor; 4 DOF plus gimballing (time)	Mr. John A. Hoffman Paragon Pacific Incorporated 1601 E. El Segundo Boulevard El Segundo, CA 90245
REXOR-WT	System; multi-DOF (time)	Mr. Robert E. Donham Dept 75-21, Bldg. 360, Plant B-6 Lockheed-California Company Burbank, CA 91520
GETSS	System; multi-DOF (freq.)	Mr. Clyde Stahle General Electric Space Division Box 8661 Philadelphia, PA 19101
F-762	System; multi-DOF, (time)	Dr. Richard Bielawa United Technologies Research Center East Hartford, CT 06108
MOSTAS	System; multi-DOF, (time/freq.)	Mr. John A. Hoffman Paragon Pacific Incorporated 1601 E. El Segundo Boulevard El Segundo, CA 90245

[a]Degrees of freedom

Table 2. - Empirical constants for calculating cyclic blade loads using MOSTAB-WTE (nominal + 1 σ, based on data obtained prior to November, 1976).

Yaw drive type	Rotor speed, rpm	Empirical constants	
		Flatwise,[a] α_y	Edgewise,[b] α_z
Single	40	1.2	0.5-0.6
Single	20	1.0	0.2
Locked	40	1.0	0.1
Dual (predicted)	40	1.1	0.3

[a] $\delta M_{y,WTE} = \alpha_y \, \delta M_{y,WT}$, in which WT signifies results from MOSTAB-WT code

[b] $\delta M_{z,WTE} = \delta M_{z,WT} + \alpha_z \, \delta M_{y,WTE}$

Table 3. - Harmonic analysis of Mod-0 Data Case I test results (envelope of three consecutive cycles).

Harmonic number	Flatwise moment, M_y				Edgewise moment, M_z			
	Amplitude, lb-ft		Phase angle, deg		Amplitude, lb-ft		Phase angle, deg	
	Bounds	Average	Bounds	Average	Bounds	Average	Bounds	Average
(a) Station 40 (5% span), Blade No. 2.								
All[a]	66,000	65,000	--	--	58,000	55,500	--	--
	64,000		--		53,000		--	
1P	31,200	31,200	29	24	42,400	42,500	-4	-2
	31,200		20		42,600		-1	
2P	25,500	25,700	20	23	7,200	5,200	173	160
	25,900		26		3,100		146	
3P	16,400	17,400	-50	-38	11,400	11,600	-14	-12
	18,400		-26		11,800		-10	
4P	8,700	7,100	-77	-70	2,500	2,400	154	144
	5,500		-64		2,200		134	
5P	8,600	7,800	-112	-113	13,900	13,800	107	109
	7,000		-114		13,800		111	
6P	3,800	3,000	-133	-126	3,000	2,200	-145	-150
	2,200		-118		1,400		-155	
(b) Station 370 (49% span), Blade No. 2.								
All	18,000	18,400	--	--	16,200	15,500	--	--
	18,900		--		14,800		--	
1P	8,100	8,800	29	23	7,800	8,000	-6	-8
	9,600		19		8,200		-10	
2P	6,000	6,200	33	30	3,000	2,200	-166	-166
	6,300		29		1,500		-165	
3P	4,300	4,400	-50	-38	3,700	4,100	-15	-14
	4,600		-26		4,500		-14	
4P	800	1,100	-93	-66	500	400	-117	-127
	1,400		-38		200		-137	
5P	3,900	3,900	-146	-132	5,600	5,200	88	91
	3,900		-117		4,800		94	
6P	500	700	-142	-143	700	400	163	170
	900		-144		200		176	

[a]Cyclic load, δM: (max-min)/2.

Table 4. - Harmonic analysis of Mod-0 Data Case IV test results.
(envelope of three consecutive cycles).

Harmonic number	Flatwise moment, M_y				Edgewise moment, M_z			
	Amplitude, lb-ft		Phase angle, deg		Amplitude, lb-ft		Phase angle, deg	
	Bounds	Average	Bounds	Average	Bounds	Average	Bounds	Average
(a) Station 40 (5% span), Blade No. 1.								
All[a]	30,000	30,000	--	--	44,000	43,000	--	--
	30,000		--		42,000		--	
1P	19,700	20,600	-154	-149	43,300	43,200	-180	-180
	21,600		-144	(31)[b]	43,000		179	(0)
2P	10,100	10,800	-14	-10	1,300	1,400	-91	-124
	11,400		-7		1,400		-157	(56)
3P	8,100	6,800	83	61	5,200	5,300	-150	-165
	5,400		39	(-119)	5,400		180	(15)
4P	3,500	3,600	-124	-122	3,900	4,000	54	61
	3,800		-120		4,000		68	(-119)
5P	1,800	1,900	17	25	3,300	2,600	-36	-22
	2,000		33	(-155)	2,000		-8	(158)
6P	2,300	2,300	-133	-102	1,700	1,200	-177	158
	2,300		-71		600		132	(-22)
(b) Station 40 (5% span), Blade No. 2.								
All	25,000	28,500	--	--	40,000	40,500	--	--
	32,000		--		41,000		--	
1P	18,100	19,500	23	21	41,200	41,400	-5	-4
	20,900		19		41,700		-4	
2P	7,600	8,800	10	10	1,200	1,600	116	116
	9,900		9		2,000		115	
3P	2,300	5,800	-59	-103	4,600	5,000	-13	-5
	9,300		-147		5,500		3	
4P	2,500	3,400	-104	-102	2,900	3,100	-128	-131
	4,300		-100		3,300		-134	
5P	1,800	2,000	-146	-149	1,500	2,400	137	134
	2,300		-152		3,200		132	
6P	1,000	1,200	-93	-100	800	600	92	96
	1,400		-108		500		101	

[a]Cyclic load, δM: (max-min)/2.
[b]Adjusted for comparison with Blade No. 2.

Table 4. - Concluded.

Harmonic number	Flatwise moment, M_y				Edgewise moment, M_z			
	Amplitude, lb-ft		Phase angle, deg		Amplitude, lb-ft		Phase angle, deg	
	Bounds	Average	Bounds	Average	Bounds	Average	Bounds	Average
(c) Station 370 (49% span), Blade No. 2.								
All	8,800	9,800	--	--	7,500	7,500	--	--
	10,800		--		7,500		--	
1P	5,000	6,200	19	14	7,000	7,100	-3	-4
	7,300		10		7,200		-5	
2P	2,200	2,400	9	0	500	500	147	151
	2,500		-10		500		155	
3P	900	1,800	-71	-111	1,500	1,400	-8	-7
	2,600		-151		1,200		-6	
4P	800	1,000	-129	-136	800	700	-142	-134
	1,200		-143		600		-127	
5P	700	600	179	176	700	700	147	136
	500		173		700		125	
6P	100	100	-96	17	200	200	108	96
	200		130		200		85	

Table 5. - Comparison of measured and calculated cyclic moment loads for Mod-0 Data Cases I and IV.

Source		Cyclic moment loads, ±lb-ft			
		Flatwise, δM_y		Edgewise, δM_z	
		Sta 40	Sta 370	Sta 40	Sta 370

(a) Data Case I

Test data	Nominal	64,000	19,000	64,000	16,200
	Actual	65,000	18,400	55,500	15,400
MOSTAB rotor codes	-WT	64,200	19,000	38,600	8,100
	-WTE	77,000	22,800	77,100	19,500
	-HFW	63,700	18,800	42,500	9,400
REXOR-WT		61,500	19,000	60,000	14,100
GETSS		76,000	22,000	51,000	17,000
F-762		69,000	19,500	50,500	12,700
MOSTAS		59,200	18,400	52,500	12,600

(b) Data Case IV

Test data	Nominal	35,000	10,200	40,000	8,100
	Actual	29,200	9,800	41,800	7,500
MOSTAB rotor codes	-WT	41,900	12,200	37,400	7,500
	-WTE	41,900	12,200	41,600	8,700
	-HFW	40,800	11,900	40,000	8,400
REXOR-WT		34,000	9,400	39,000	7,800
GETSS		32,200	8,800	39,000	8,200
F-762		30,500	9,200	42,000	9,000
MOSTAS		42,600	12,500	38,900	8,200

Table 6. - Comparison of relative cyclic moment loads, normalized with respect to nominal cyclic loads.

Source		Relative cyclic moment loads			
		Flatwise[a]		Edgewise[b]	
		Sta 40	Sta 370	Sta 40	Sta 370
(a) Data Case I					
Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	1.02	0.97	0.87	0.95
MOSTAB rotor codes	-WT	1.00	1.00	0.60	0.50
	-WTE	1.20	1.20	1.20	1.20
	-HFW	1.00	0.99	0.66	0.58
REXOR-WT		0.96	1.00	0.94	0.87
GETSS		1.19	1.16	0.80	1.05
F-762		1.08	1.03	0.78	0.77
MOSTAS		0.92	0.97	0.82	0.78
(b) Data Case IV					
Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	0.83	0.96	1.05	0.93
MOSTAB rotor codes	-WT	1.20	1.20	0.94	0.93
	-WTE	1.20	1.20	1.04	1.07
	-HFW	1.17	1.17	1.00	1.04
REXOR-WT		0.97	0.92	0.98	0.96
GETSS		0.92	0.86	0.98	1.01
F-762		0.87	0.91	1.05	1.11
MOSTAS		1.22	1.23	0.97	1.01

[a] $\delta M_y / \delta M_{y,nom}$

[b] $\delta M_z / \delta M_{z,nom}$

Table 7. - Calculation of zero error in test data using zero harmonic (time average) moments from MOSTAB and REXOR-WT as standards.

Source	Flatwise zero harmonic, lb-ft				Edgewise zero harmonic, lb-ft			
	Station 40		Station 370		Station 40		Station 370	
	Bounds	Average	Bounds	Average	Bounds	Average	Bounds	Average
(a) Data Case I								
MOSTAB	36,700	33,500	7,100	6,000	-16,800	-16,600	-4,000	-3,800
REXOR-WT	30,300		4,900		-16,400		-3,600	
Test, Blade 2	28,000	35,400	3,400	5,700	-24,300	-20,900	-6,200	-4,600
	42,900		8,000		-17,500		-3,000	
Error		1,900		-300		-4,300		-800
(b) Data Case IV								
MOSTAB	27,400	26,200	3,600	3,200	-14,000	-14,600	-3,200	-3,200
REXOR-WT	25,000		2,800		-15,300		-3,200	
Test, Blade 1	400	8,200	-----	-----	-14,600	-12,400	-----	-----
	16,400		-----		-10,100		-----	
Test, Blade 2	2,800	11,200	4,400	-2,000	-15,300	-13,200	-1,400	-800
	19,600		400		-11,000		-100	
Error		-16,500		-5,200		1,800		2,400

Table 8. - Calculation of peak nominal moment loads for Mod-0 Data Cases I and IV.

(a) Data Case I

Component		Bending moment load, lb-ft			
		Flatwise, M_y		Edgewise, M_z	
		Sta 40	Sta 370	Sta 40	Sta 370
Steady (actual) Blade 2	max	67,000	13,100	-24,000	-5,000
	min	58,000	9,500	-18,000	-2,200
	aver	62,500	11,300	-21,000	-3,600
Zero error		1,900	-300	-4,300	-800
Steady (nom)		60,600	11,600	-16,700	-2,800
Cyclic (nom)		±64,000	±19,000	±64,000	±16,200
Peak (nom)[a]		124,600	30,600	80,700	19,000

[a]max absolute value during cycle

(b) Data Case IV

Steady (actual) Blades 1 and 2	max	22,000	----	-15,000	----
	min	10,000	----	-10,000	----
	max	20,000	2,800	-15,000	-1,000
	min	8,000	-3,200	-10,000	500
	aver	15,000	-200	-12,500	-200
Zero error		-16,500	-5,200	1,800	2,400
Steady (nom)		31,500	5,000	-14,300	-2,600
Cyclic (nom)		±35,000	±10,200	±40,000	±8,100
Peak (nom)		66,500	15,200	54,300	-10,700

Table 9. - Comparison of measured and calculated peak moment loads for Mod-0 Data Cases I and IV.

Source		Peak moment loads, lb-ft			
		Flatwise[a]		Edgewise[b]	
		Sta 40	Sta 370	Sta 40	Sta 370
(a) Data Case I					
Test data	Nominal	124,600	30,600	80,700	19,000
	Actual	125,600	30,200	72,200	18,200
MOSTAB rotor codes	-WT	126,400	34,400	53,000	10,900
	-WTE	139,200	38,200	91,500	22,300
	-HFW	127,000	34,500	63,100	13,800
REXOR-WT		119,000	32,000	72,000	16,200
GETSS		122,000	29,500	58,000	21,000
F-762		138,000	36,500	68,000	18,000
MOSTAS		109,200	29,900	69,200	17,800
(b) Data Case IV					
Test data	Nominal	66,500	15,200	54,300	10,700
	Actual	50,700	14,800	56,100	10,100
MOSTAB rotor codes	-WT	81,600	19,800	50,800	10,300
	-WTE	81,600	19,800	50,800	10,300
	-HFW	81,100	19,700	57,400	12,100
REXOR-WT		68,000	15,100	52,000	10,000
GETSS		50,300	10,200	42,000	12,500
F-762		61,000	14,000	55,100	13,600
MOSTAS		68,200	16,000	54,000	11,500

[a] $|M_y|_{max}$

[b] $|M_z|_{max}$

Table 10. - Relative peak moment loads, normalized with respect to nominal peak loads.

Source		Relative peak moment loads			
		Flatwise[a]		Edgewise[b]	
		Sta 40	Sta 370	Sta 40	Sta 370
(a) Data Case I					
Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	1.01	0.98	0.89	0.96
MOSTAB rotor codes	-WT	1.01	1.12	0.66	0.57
	-WTE	1.12	1.25	1.13	1.17
	-HFW	1.02	1.13	0.78	0.73
REXOR-WT		0.96	1.05	0.89	0.85
GETSS		0.98	0.96	0.72	1.11
F-762		1.11	1.19	0.84	0.95
MOSTAS		0.88	0.98	0.86	0.94
(b) Data Case IV					
Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	0.76	0.97	1.03	0.94
MOSTAB rotor codes	-WT	1.23	1.30	0.94	0.96
	-WTE	1.23	1.30	0.94	0.96
	-HFW	1.22	1.30	1.06	1.13
REXOR-WT		1.02	0.99	0.96	0.93
GETSS		0.76	0.67	0.77	1.17
F-762		0.92	0.92	1.01	1.27
MOSTAS		1.03	1.05	0.99	1.07

[a] $\left|M_y\right|_{max} / \left|M_{y,nom}\right|_{max}$

[b] $\left|M_z\right|_{max} / \left|M_{z,nom}\right|_{max}$

Table 11. - Summary of load ratios obtained using various computer codes and Mod-0 wind turbine test data.

Code Type and Name		Goal of Calc. Load	Blade Load Ratio [a]	
			Average	RMS Dev. [b]
Rotor Codes	MOSTAB-WTE	Nom. + 1σ	1.15	± 0.10
	MOSTAB-HFW	Nom.	1.00	± 0.20
	MOSTAB-WT	"	0.95	± 0.24
System Codes	F-762	"	0.99	± 0.14
	MOSTAS	"	0.98	± 0.12
	REXOR-WT	"	0.95	± 0.05
	GETSS	"	0.94	± 0.16

[a] Calculated-to-nominal measured; based on 16 ratios combining 2 data cases, 2 blade stations, flatwise and edgewise directions, and cyclic and peak bending moments.

[b] Root-mean-square deviation; includes approximately 11 of 16 ratios.

Table 12. - Comparison of cyclic moments and harmonic amplitudes from various sources for Mod-0 Data Case I.

Harmonic number	Amplitude of moment load, by source, lb-ft							
	Test (aver)	MOSTAB rotor codes			System codes			
		-WT	-WTE	-HFW	REXOR-WT	GETSS	F-762	MOSTAS
(a) Station 40 (5% span), flatwise bending								
All[a]	65,000	64,200	77,000	63,700	61,500	76,000	69,000	59,200
1P	31,200	40,500	48,600	38,700	29,800	51,000	38,800	35,600
2P	25,700	18,600	22,300	18,700	23,700	24,200	26,500	16,500
3P	17,400	20,000	24,000	20,800	20,500	20,200	10,700	20,800
4P	7,100	7,900	9,500	8,600	6,600	6,800	7,600	8,900
5P	7,800	2,800	3,400	3,300	5,100	6,500	7,700	3,900
6P	3,000	1,100	1,300	1,400	600	900	6,000	1,200
(b) Station 40 (5% span), edgewise bending								
All	55,500	38,600	77,100	42,500	60,000	51,000	50,500	52,500
1P	42,500	35,000	60,300	38,300	37,500	41,100	37,300	45,400
2P	5,200	1,900	0	1,900	3,600	2,800	7,600	1,400
3P	11,600	4,400	21,700	7,000	26,900	14,800	9,200	19,900
4P	2,400	3,800	0	6,300	1,600	1,500	6,100	500
5P	13,800	2,700	21,700	1,100	4,400	1,000	5,800	6,300
6P	2,200	2,300	0	300	800	300	5,700	500
(c) Station 370 (49% span), flatwise bending								
All	18,400	19,000	22,800	18,800	19,000	22,000	19,500	18,400
1P	8,800	10,900	13,100	10,300	7,500	11,700	11,300	9,500
2P	6,200	5,000	6,000	5,100	6,800	6,200	7,400	4,300
3P	4,400	6,300	7,600	6,600	7,400	6,500	3,500	6,900
4P	1,100	3,100	3,700	3,400	2,400	2,200	2,300	3,300
5P	3,900	1,500	1,800	1,700	2,600	1,700	2,100	1,900
6P	700	800	1,000	1,000	500	400	1,800	900
(d) Station 370 (49% span), edgewise bending								
All	15,400	8,100	19,500	9,400	14,100	17,000	12,700	12,600
1P	8,000	6,600	14,200	7,300	6,900	7,500	7,300	9,500
2P	2,200	900	0	500	1,300	1,300	2,600	900
3P	4,100	1,800	6,100	2,000	7,300	3,300	2,400	5,700
4P	400	1,300	0	2,000	600	400	1,900	300
5P	5,200	900	6,100	300	2,800	400	2,100	1,900
6P	400	700	0	100	300	200	2,100	100

[a]cyclic load, $\delta M = (\max - \min)/2$

Table 13. - Comparison of cyclic moments and harmonic amplitudes from various sources for Mod-O Data Case IV.

Harmonic number	Amplitude of moment load, by source, lb-ft							
	Test (aver)	MOSTAB rotor codes			System codes			
		-WT	-WTE	-HFW	REXOR-WT	GETTS	F-762	MOSTAS
(a) Station 40 (5% span), flatwise moments								
All[a]	29,200	41,900	41,900	40,800	34,000	32,200	30,500	42,600
1P	20,000	30,400	30,400	28,700	25,600	26,100	20,600	29,900
2P	9,800	8,900	8,900	8,800	12,100	7,400	10,400	10,200
3P	6,200	9,600	9,600	10,100	5,500	2,800	7,000	10,400
4P	3,500	3,800	3,800	4,200	2,600	2,300	3,200	6,200
5P	2,000	1,400	1,400	1,600	1,500	1,100	1,500	1,600
6P	1,800	500	500	600	300	---	1,200	700
(b) Station 40 (5% span), edgewise moments								
All	41,800	37,400	41,600	40,000	39,000	39,000	42,000	38,900
1P	42,300	36,100	43,400	38,800	38,800	37,500	37,600	38,500
2P	1,500	900	0	1,500	1,500	600	2,950	1,100
3P	5,200	2,000	6,000	4,300	2,500	3,400	6,000	2,700
4P	3,600	1,900	0	3,500	2,000	500	170	700
5P	2,500	1,500	6,000	800	4,700	600	2,200	1,600
6P	900	1,200	0	500	600	---	1,300	300
(c) Station 370 (49% span), flatwise moments								
All	9,800	12,200	12,200	11,900	9,400	8,800	9,250	12,500
1P	6,200	8,400	8,400	7,700	6,800	7,700	6,500	8,100
2P	2,400	2,400	2,400	2,500	3,500	2,300	3,000	2,600
3P	1,800	3,000	3,000	3,200	1,700	800	1,900	3,300
4P	1,000	1,500	1,500	1,700	1,000	900	1,100	2,200
5P	600	700	700	800	500	300	560	900
6P	100	400	400	500	300	---	220	500
(d) Station 370 (49% span), edgewise moments								
All	7,500	7,500	8,700	8,400	7,800	8,200	9,000	8,200
1P	7,100	6,900	8,900	7,400	7,300	7,600	7,500	7,500
2P	500	400	0	300	600	2,300	1,000	600
3P	1,400	800	1,400	1,200	700	800	1,700	700
4P	700	400	0	1,100	600	900	60	300
5P	700	400	1,400	200	1,300	300	630	500
6P	200	400	0	100	200	---	200	100

[a]cyclic load, $\delta M = (\text{max-min})/2$

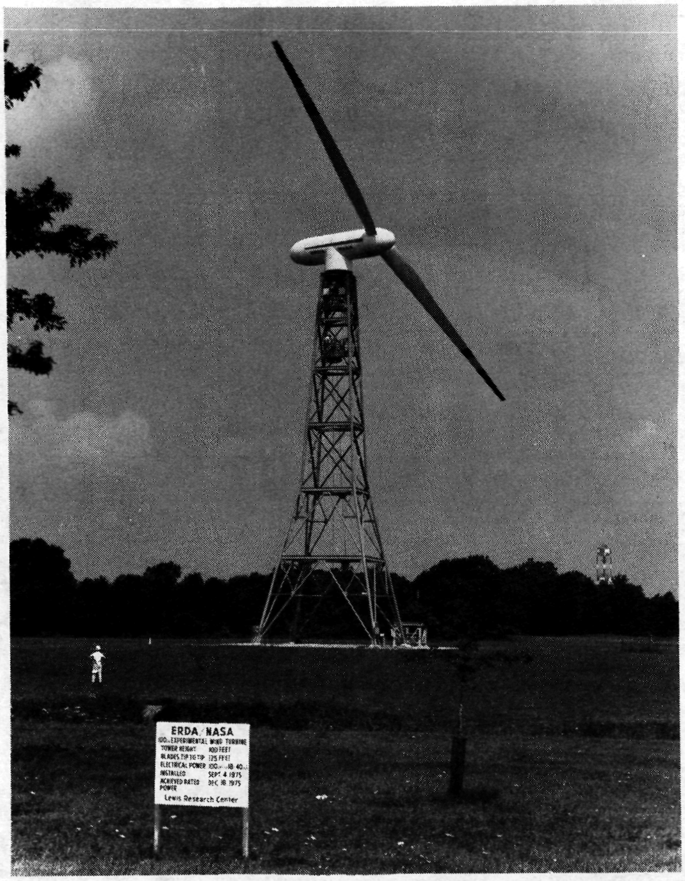
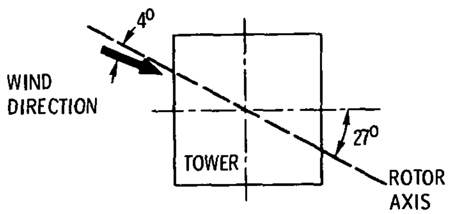
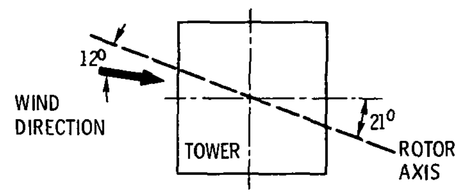


Figure 1. - ERDA/NASA 100 kW Mod-0 wind turbine, located at NASA's Plum Brook Station near Sandusky, Ohio (rated wind speed, 18 mph; rotor speed, 40 rpm; rotor diameter, 125 ft; rotor axis elevation, 100 ft).



(a) DATA CASE I. TOWER WITH STAIRS, SINGLE YAW DRIVE, AND 28 mph WIND SPEED.



(b) DATA CASE IV TOWER WITHOUT STAIRS, LOCKED YAW DRIVE, AND 25 mph WIND SPEED

Figure 2 - Schematic plan views showing Mod-0 orientation during data cases I and IV (98 to 100 kW power, 40 rpm rotor speed)

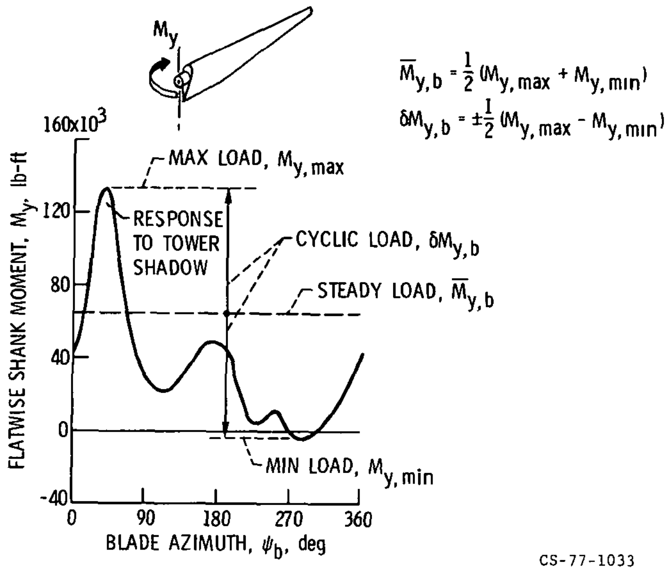


Figure 3. - Typical cycle of blade flatwise moment measured on the ERDA-NASA 100 kW Mod-0 wind turbine

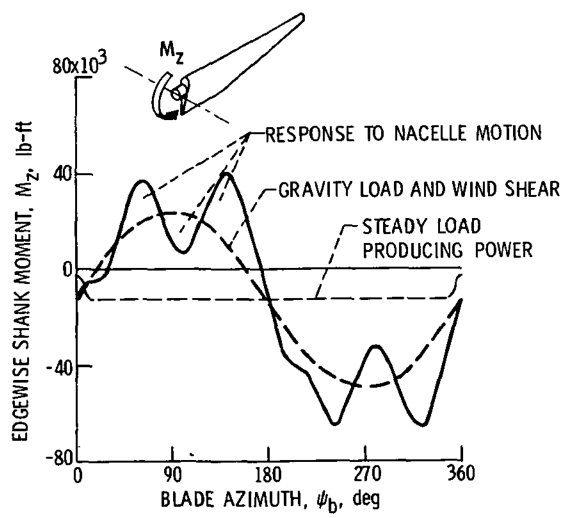


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Figure 4. - Typical cycle of blade edgewise moment measured on the Mod-0 wind turbine

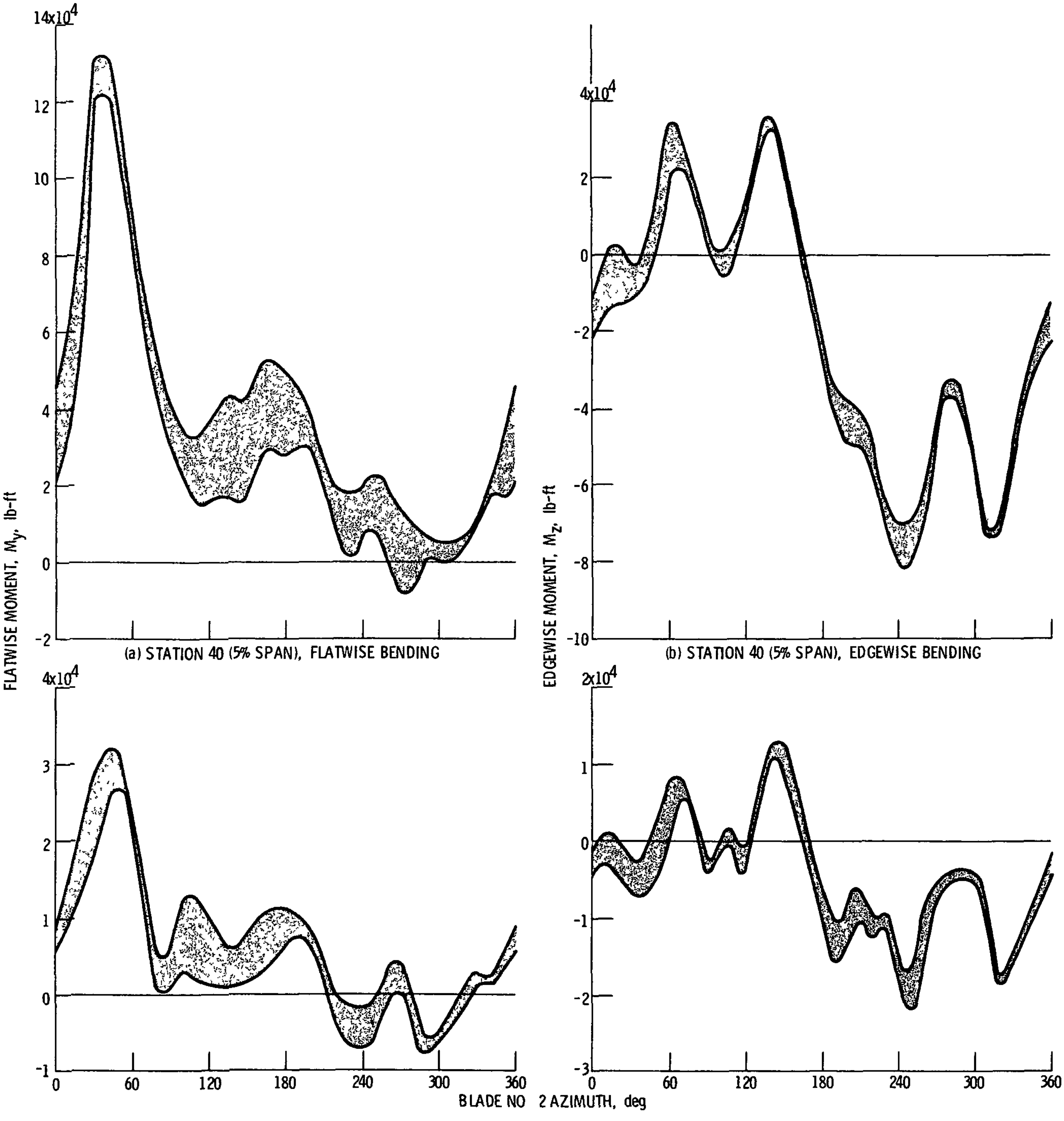
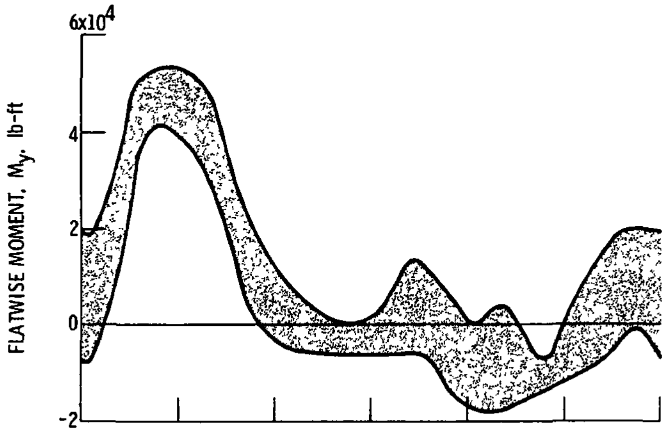
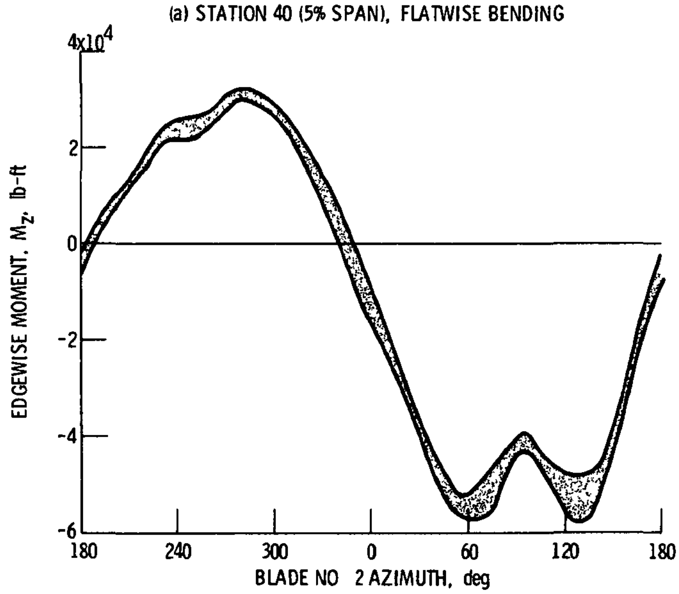


Figure 5 - Time histories of Mod-0 data case I bending loads in blade no 2 (envelopes of three consecutive revolutions)



(a) STATION 40 (5% SPAN), FLATWISE BENDING



(b) STATION 40 (5% SPAN), EDGEWISE BENDING

Figure 6. - Time histories of Mod-0 data case IV, bending moment loads in blade no. 1 (envelopes of three consecutive revolutions).

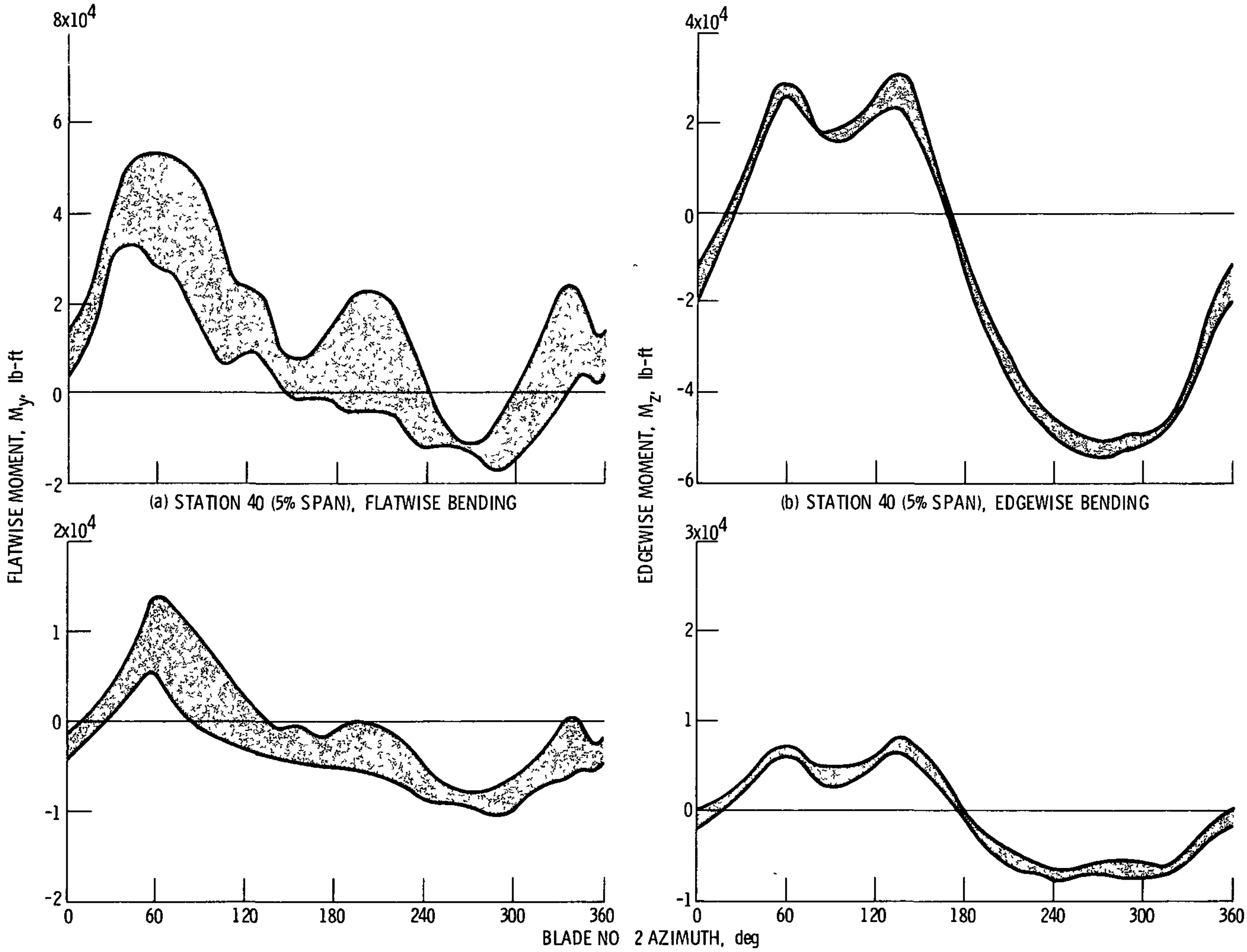


Figure 7 - Time histories of Mod-0 data case IV bending moment loads in blade no 2 (envelopes of three consecutive revolutions)

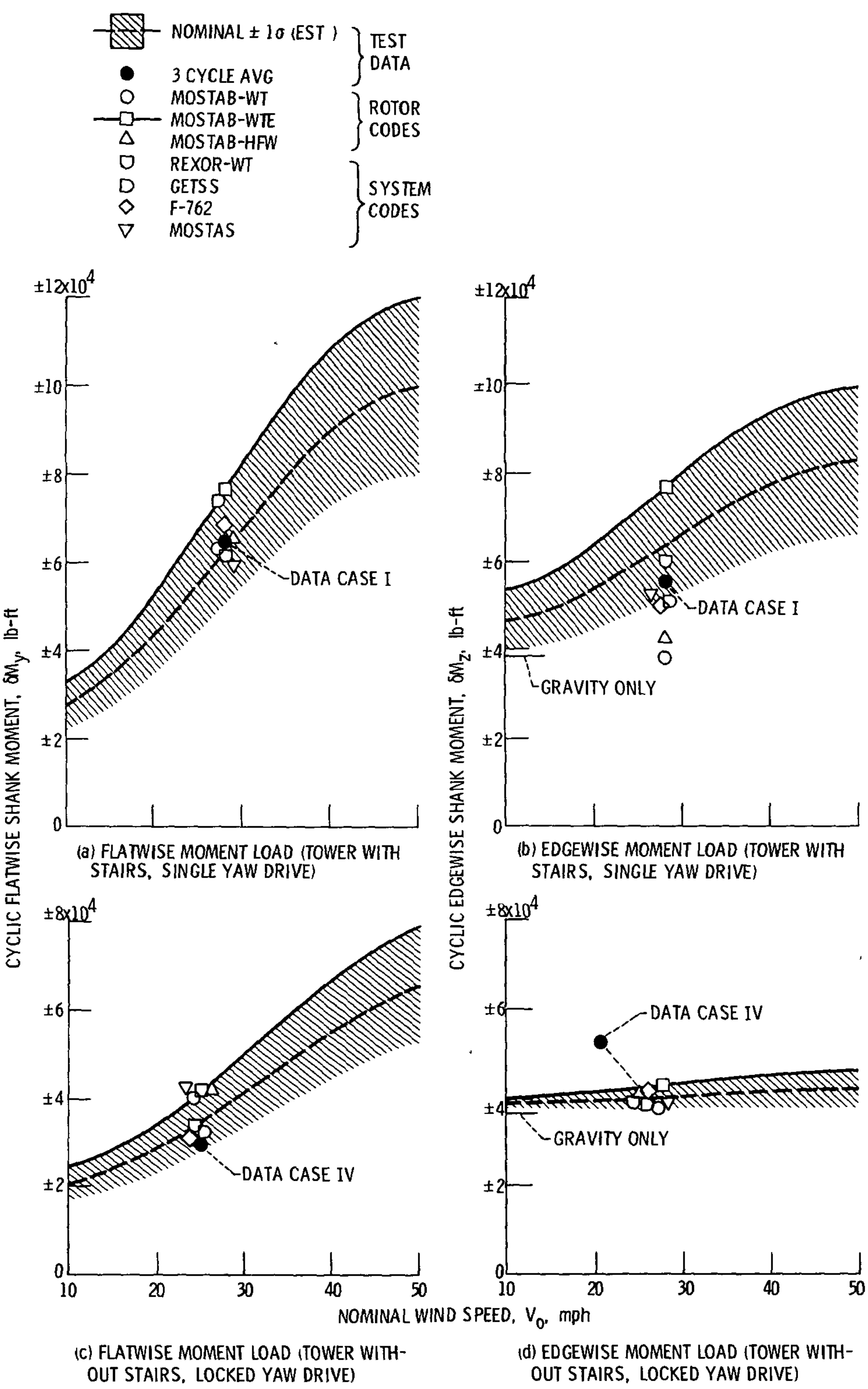


Figure 8. - Comparison of measured and calculated shank moment loads at various wind speeds (Station 40, 5% span)

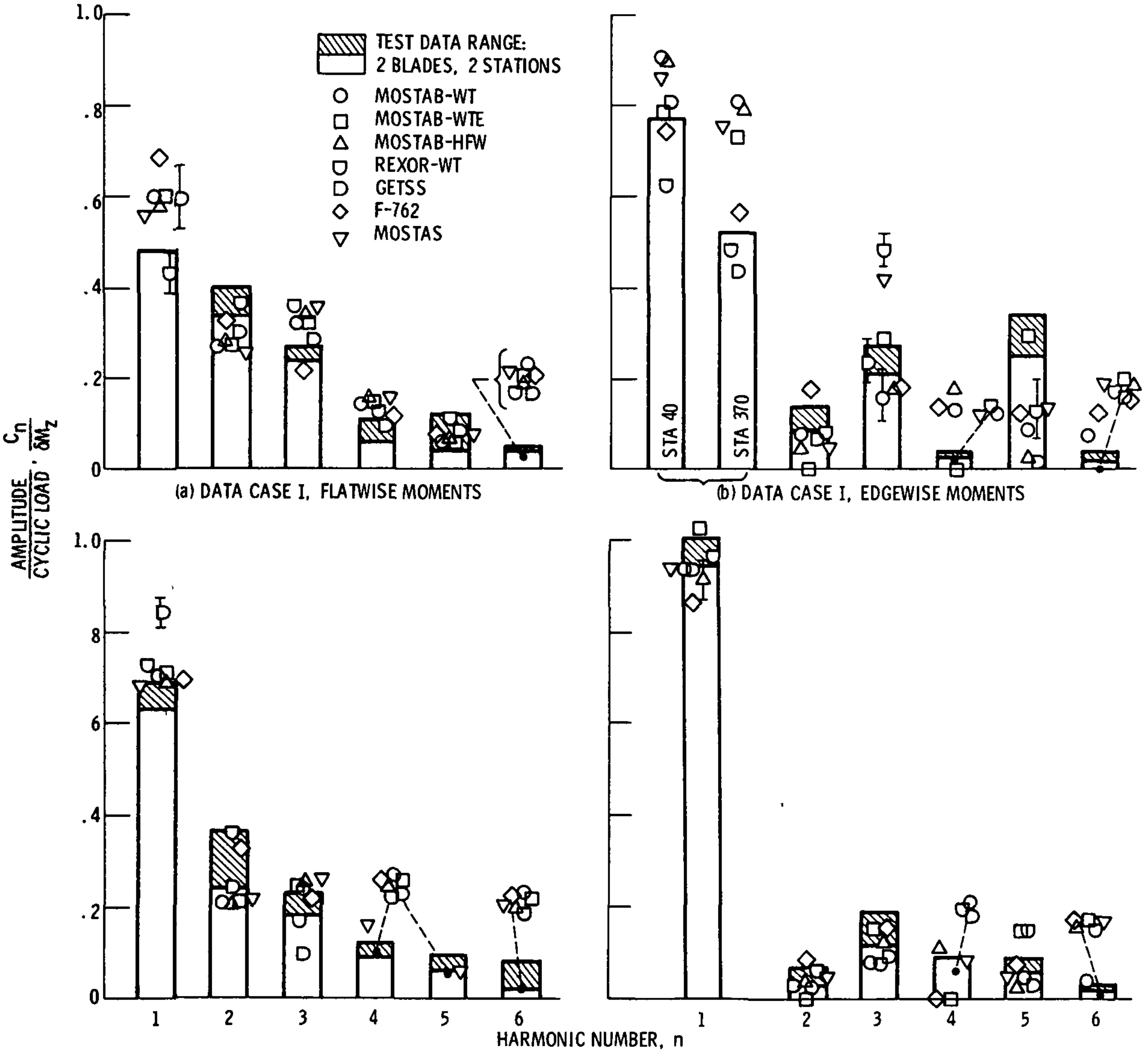
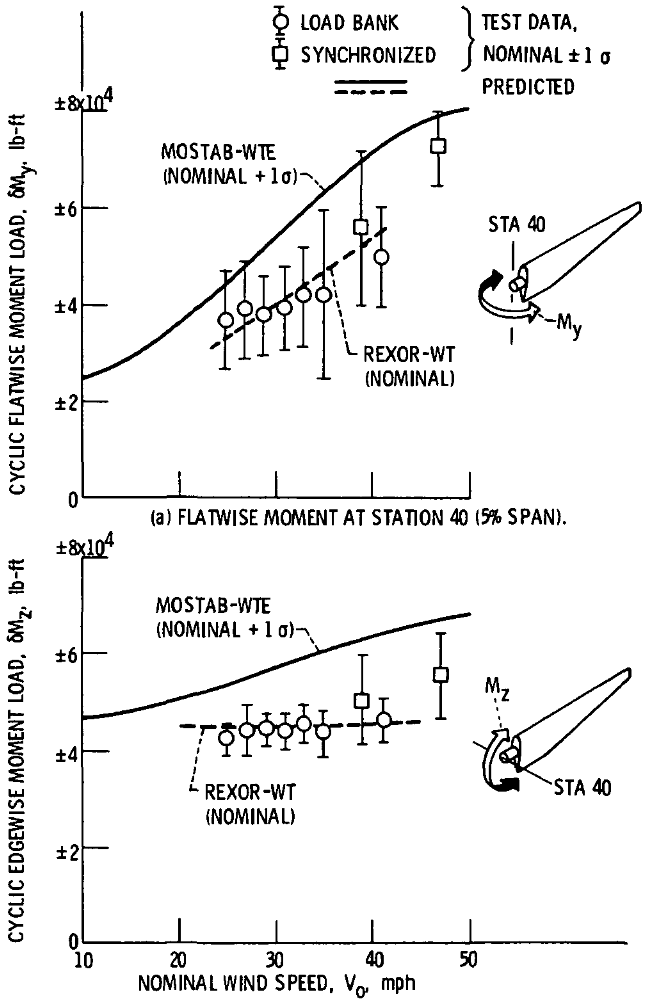


Figure 9. - Comparison of measured and calculated harmonic contents of moment load cycles. Each harmonic amplitude is normalized with respect to its total cyclic load (stations 40 and 370)



(b) EDGEWISE MOMENT AT STATION 40 (5% SPAN)

Figure 10 - Comparison of measured and predicted cyclic blade loads for the Mod-0 wind turbine with dual yaw drive installed and stairs removed.

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15. Supplementary Notes

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16. Abstract

Seven computer codes for analyzing performance and loads in large, horizontal-axis wind turbines were used to calculate blade bending moment loads for two operational conditions of the 100 kW Mod-O wind turbine. Results are compared with test data on the basis of cyclic loads, peak loads, and harmonic contents. Four of the seven codes include rotor-tower interaction and three are limited to rotor analysis. With a few exceptions, all calculated loads were within 25% of nominal test data.

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